Superfluid ³He in Motion: from Vortices to Time Crystals

Samuli Autti

Superfluid ³He in Motion: from Vortices to Time Crystals

Aalto: P.J. Heikkinen, J. Hosio, T. Kamppinen, J.T. Mäkinen, J. Nissinen, V.V. Zavjalov, G.E. Volovik, V.B. Eltsov, M.Krusius

Moscow: A.A. Soldatov, A.N. Yudin, V.V. Dmitriev

Please find our papers on arXiv

Superfluid ³He in Motion: from Vortices to Time Crystals

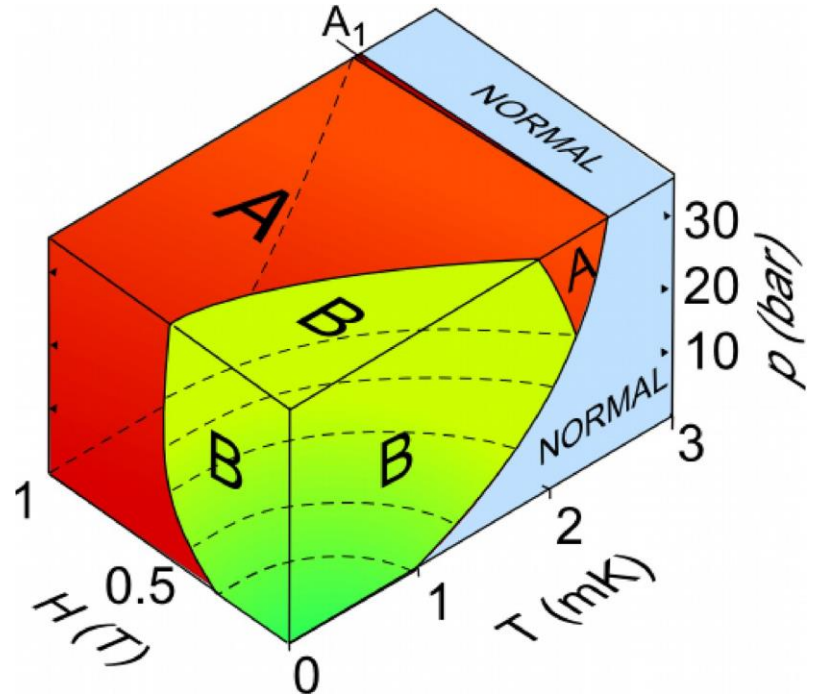*Aalto:* P.J. Heikkinen, J. Hosio, J.T. Mäkinen, J. Nissinen, V.V. Zavjalov, G.E. Volovik, V.B. Eltsov, M.Krusius

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Superfluid ^{3}He?

1. Fermions, so no BEC
   --> Cooper pairs as in superconductors?
2. Hard core repulsion
3. P-wave pairing, S=1 and L=1
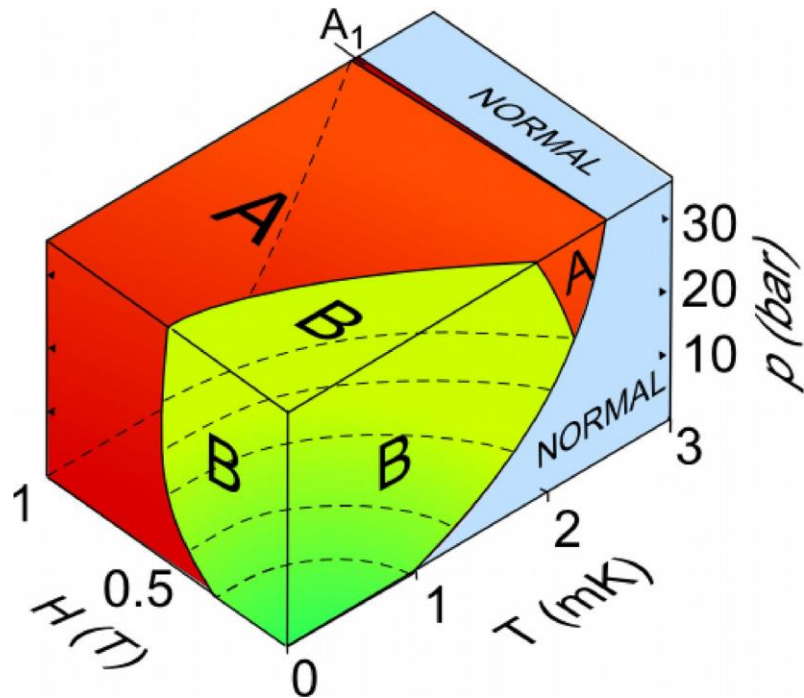4. Order parameter describing S, L, Δ, φ

Outline

1. Fermions, so no BEC
   --> Cooper pairs as in superconductors?
2. Hard core repulsion
3. P-wave pairing, S=1 and L=1
4. Order parameter describing S, L, Δ, φ

Vortices in the polar phase

Kibble-Zurek mechanism with drive and bias
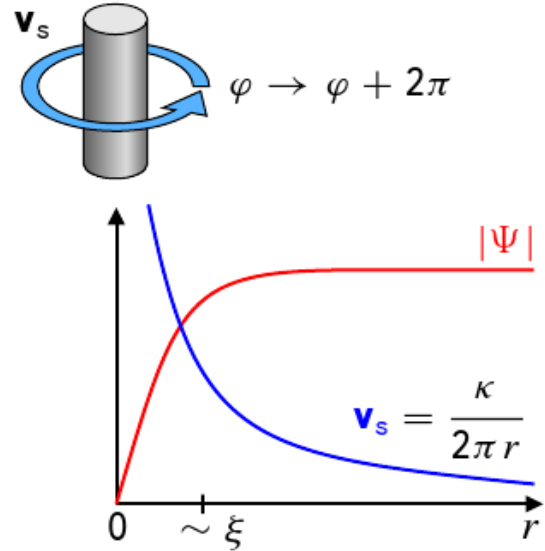
From HPD to interacting time crystals

Quantised Vortex?

Order parameter $\Psi = |\Psi| e^{i\phi}$, superfluid velocity $v_s = \dfrac{\hbar}{M} \nabla \phi$

No rotatiton: $|\Psi| > 0 \Rightarrow \nabla \times v_s \equiv 0$, however, circulation is allowed via vortices.

Circulation is quantised $\displaystyle \int v_s \cdot dr = \kappa = \dfrac{2\pi\hbar}{M}$

Core size ~ coherence length ξ

Volovik in 1976: **half-quantum vortices** exist!
- but attempts to resolve in the A phase failed

$$v_s$$
$$\varphi \to \varphi + 2\pi$$

$$|\Psi|$$

$$v_s = \frac{\kappa}{2\pi r}$$

$$0 \qquad \sim \xi \qquad \qquad r$$

$$|\Psi| \to 0 : \textbf{singular} \text{ vortex}$$

Polar phase

1. Fermions, so no BEC
   --> Cooper pairs as in superconductors?
2. Hard core repulsion
3. P-wave pairing, S=1 and L=1
4. Order parameter describing S, L, Δ, φ

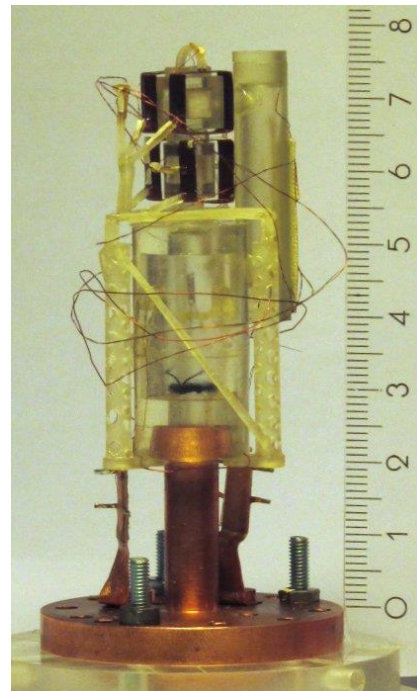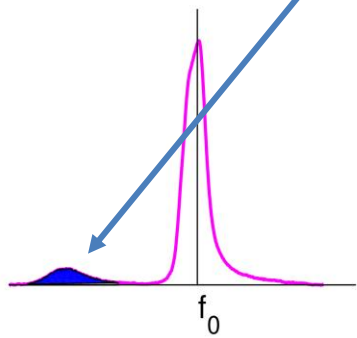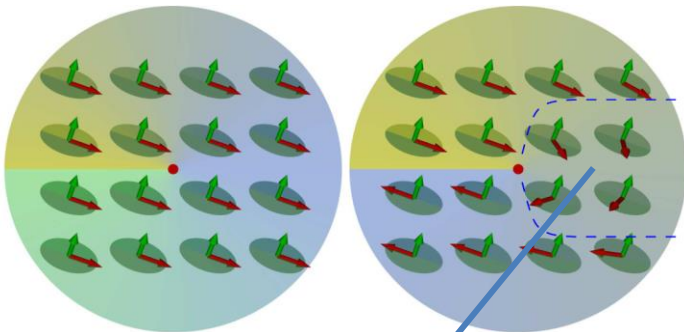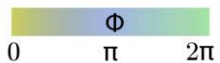Additional phases in restricted geometries
--> polar phase in 2015

Nafen

Polar phase

1. Fermions, so no BEC
   --> Cooper pairs as in superconductors?
2. Hard core repulsion
3. P-wave pairing, S=1 and L=1
4. Order parameter describing S, L, Δ, φ
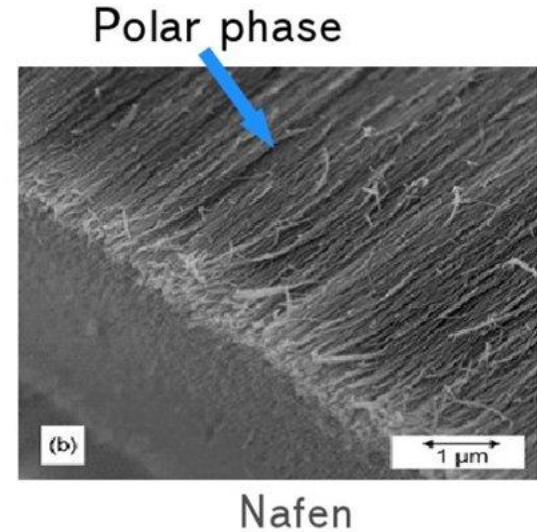
Additional phases in restricted geometries
--> polar phase in 2015

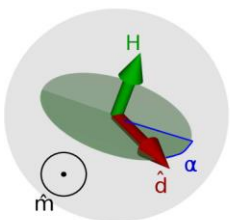Dmitriev et al, PRL **115**, 165304 (2015)
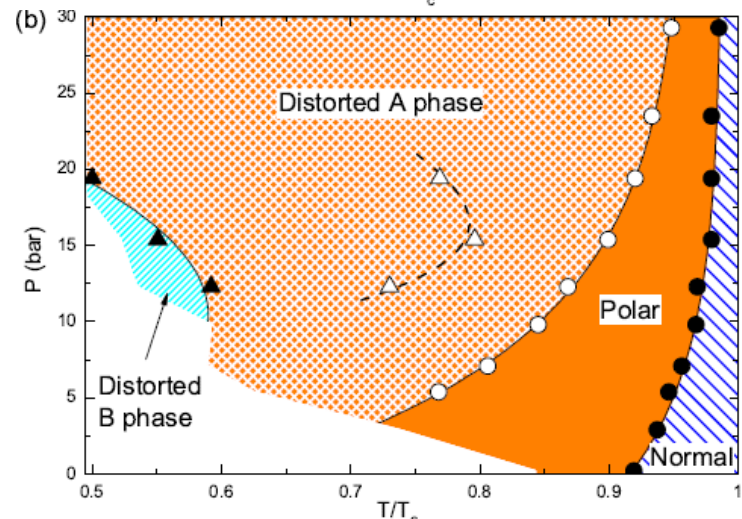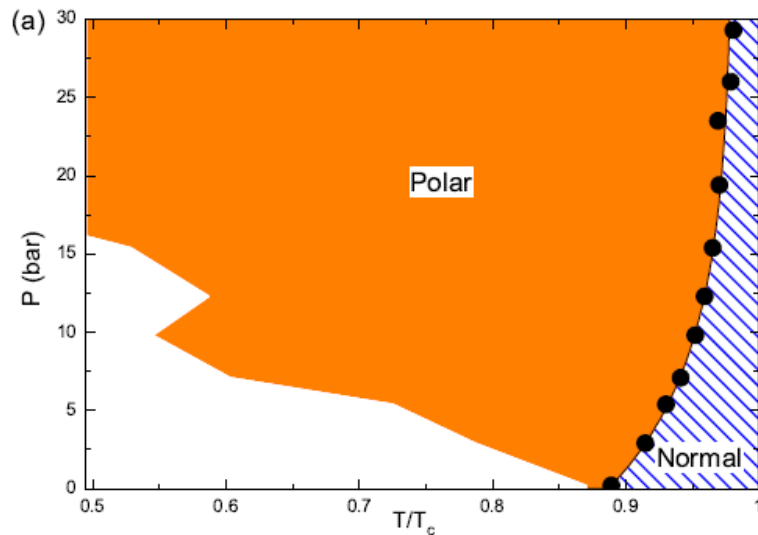
Half-quantum vortex
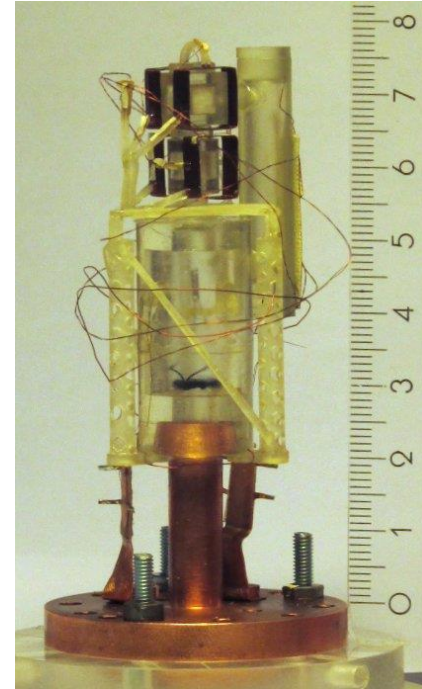
Half-quantum vortex

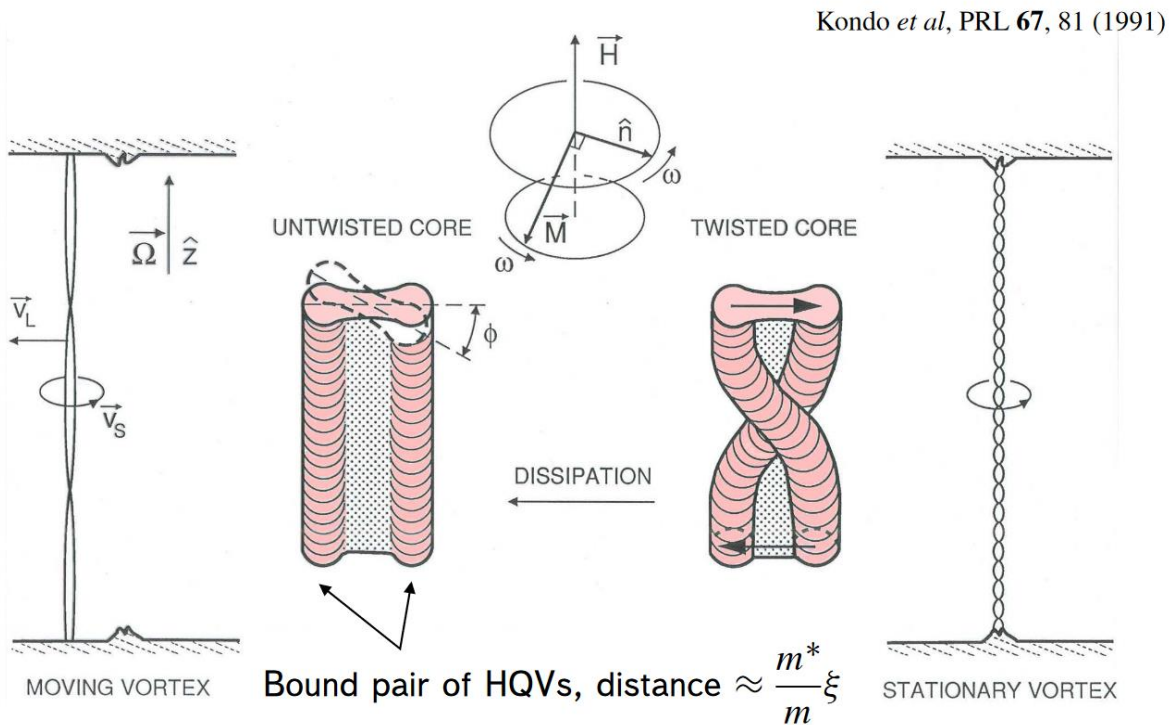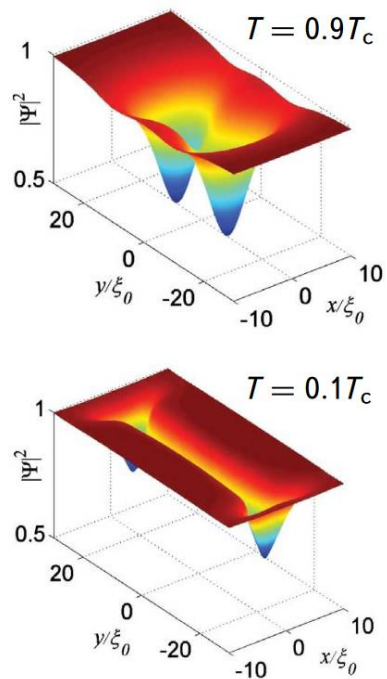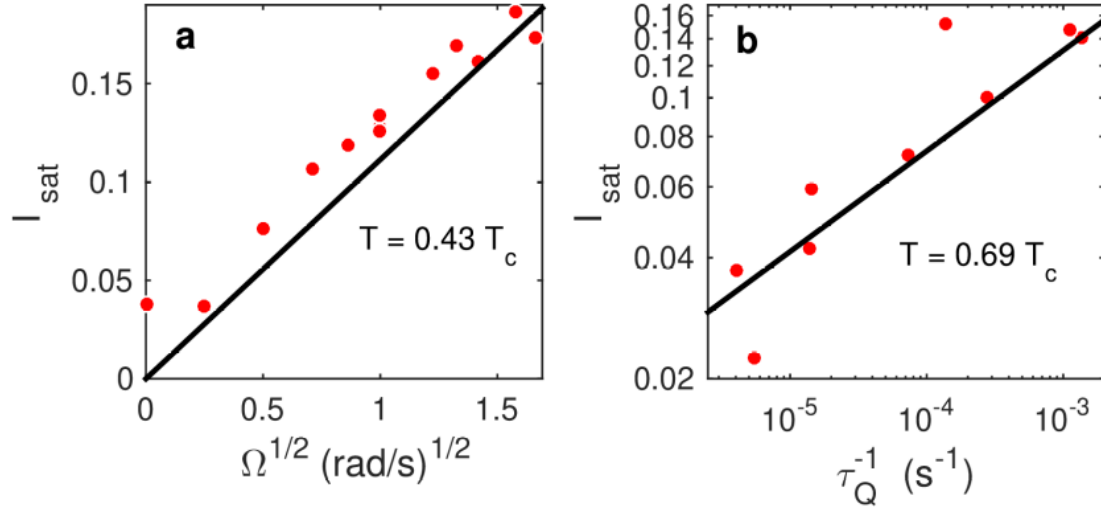**Single-quantum**   **Half-quantum**
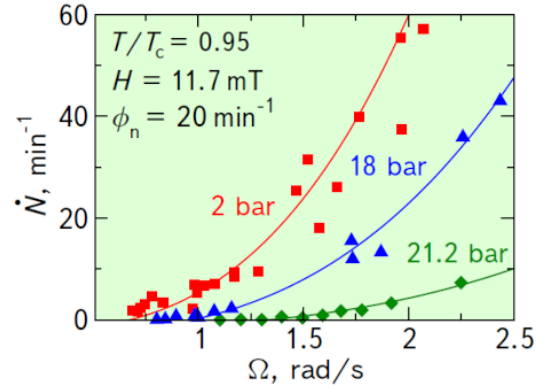
Half-quantum vortex
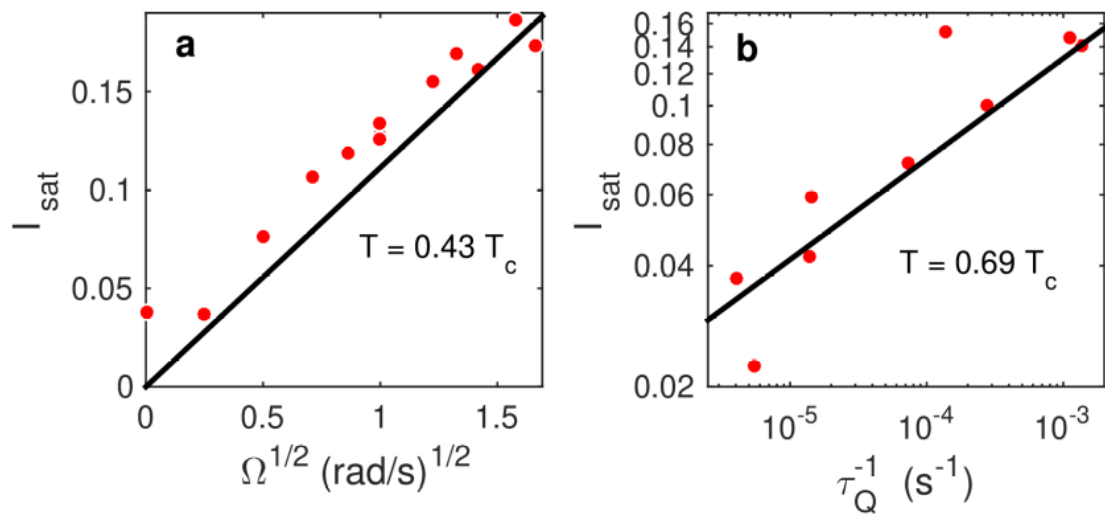
Double-core vortex in B phase

$T = 0.9T_c$

$T = 0.1T_c$

Kondo *et al*, PRL **67**, 81 (1991)

UNTWISTED CORE

TWISTED CORE

DISSIPATION

MOVING VORTEX

STATIONARY VORTEX

Bound pair of HQVs, distance $\approx \dfrac{m^*}{m}\xi$

Half-quantum vortex

Kibble-Zurek mechanism

^{3}He-B

Neutron source

v_s v_n

Ω

Ω

NMR absorption (counterflow peak)

5

on

2 2

2

9

4 4

4

3

2 1 2 1

2 1 1

4

4 2

off

20 vortices

2 min

t

$p = 2.0$ bar
$H = 11.7$ mT
$T/T_c = 0.95$
$\Omega = 1.95$ rad/s
$\phi_n = 2.7$ min^{-1}
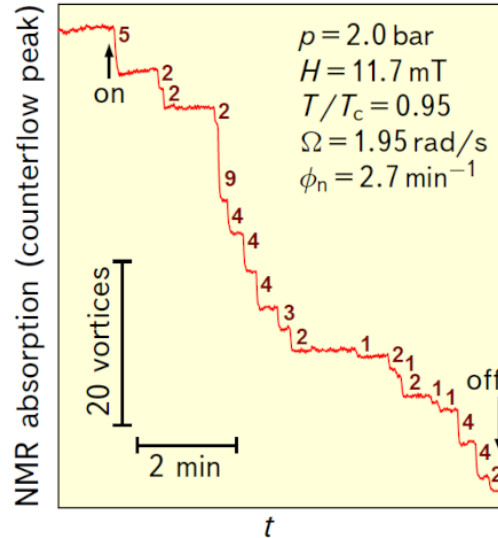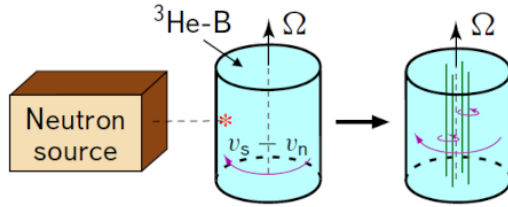
Vortex formation rate $\dot{N}$ depends on p, T, H, ϕ_n, $v_n = \Omega R$ and $v_s = \kappa N/2\pi R$

$T/T_c = 0.95$
$H = 11.7$ mT
$\phi_n = 20$ min^{-1}

$\dot{N}$, min^{-1}

18 bar

2 bar

21.2 bar

Ω, rad/s

$$\frac{dN}{dt} = \phi_n \, \mathcal{A} \left[\left(\frac{v_n - v_s}{v_{cn}(p,T,H)} \right)^3 - 1 \right]$$

Ruutu et al, Nature **382**, 334 (1996)

Kibble-Zurek combined with drive
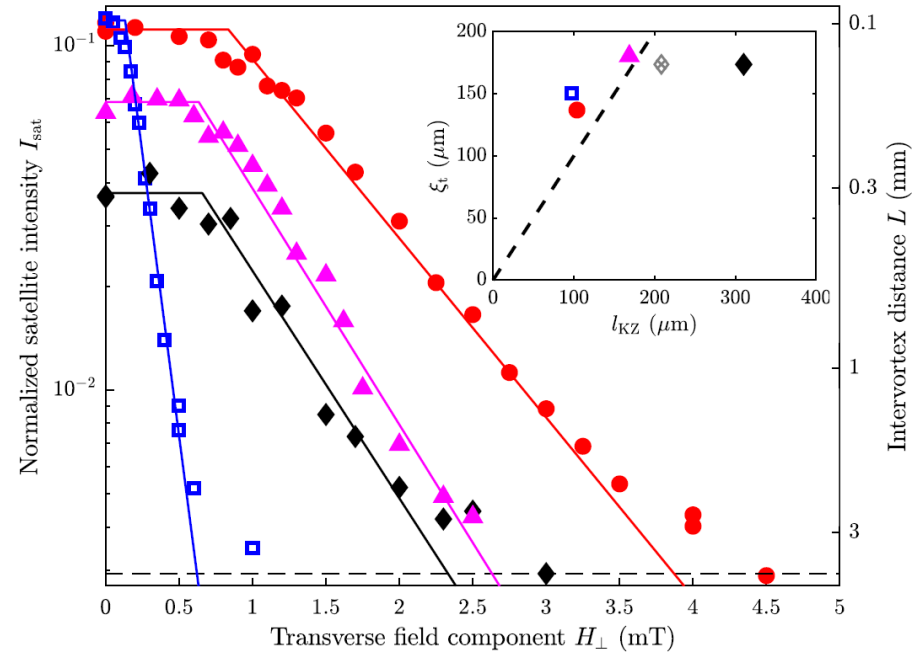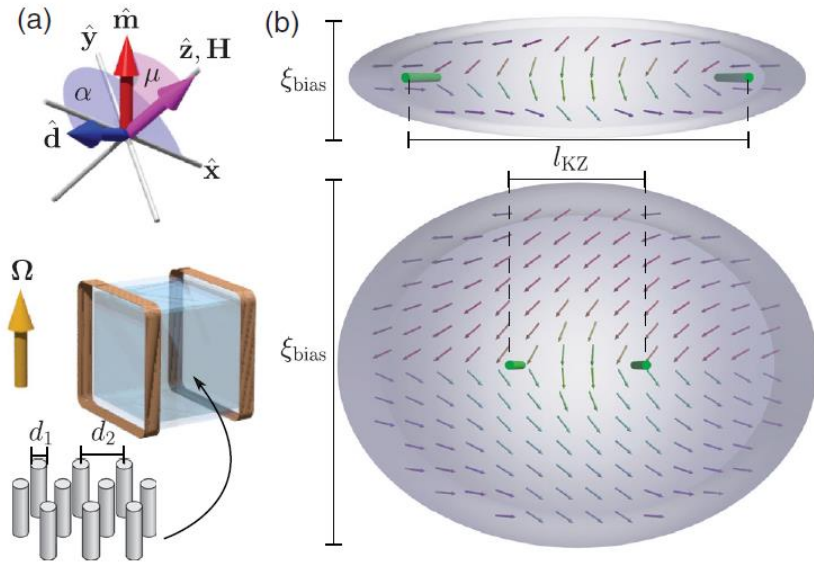
$$I_{\text{sat}} = \sqrt{I_{KZ}^2 + I_0^2 \Omega}$$

$e^{i\varphi(\mathbf{r},t)}$

linear defect will form

$\tau_Q^{-1} = 5 \cdot 10^{-3} \frac{T/T_c}{s}$

$\tau_Q^{-1} = 10^{-4} \frac{T/T_c}{s}$

I_{KZ}

I_{KZ}

I_{sat}
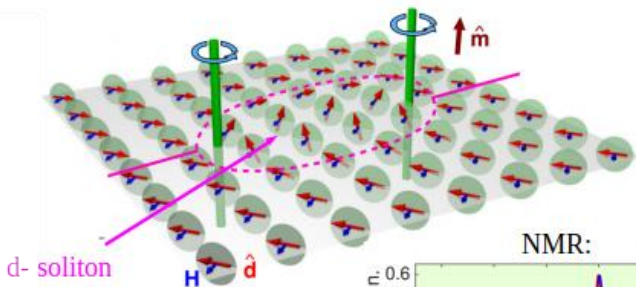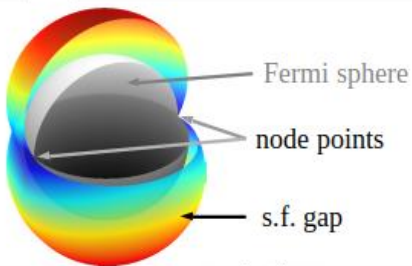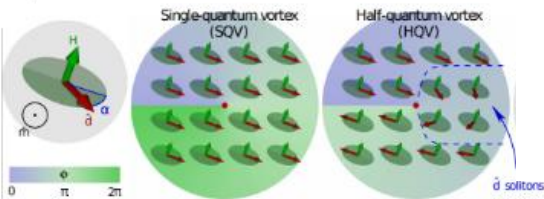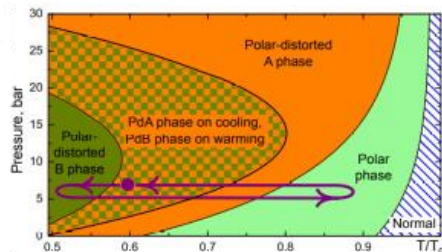
$(\Omega)^{1/2}$ (rad/s)$^{1/2}$
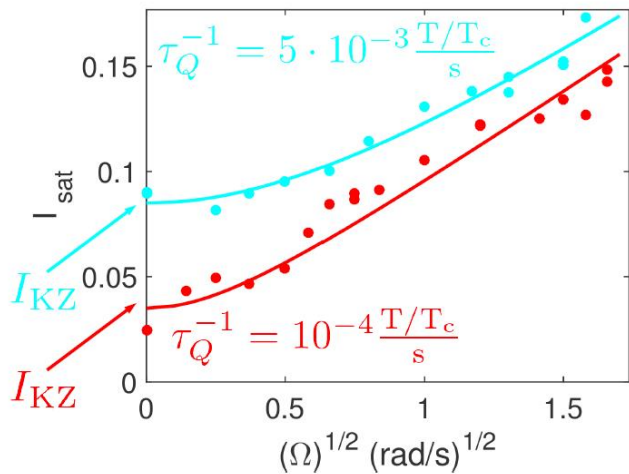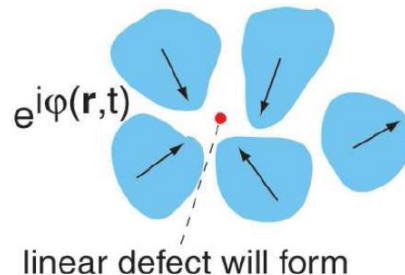
Apply:

- **Rotation drive + weak KZ**
- **Rotation drive + large KZ**

Kibble-Zurek suppressed with bias
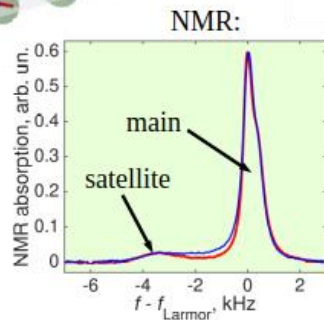
Half-quantum vortex in the PdA phase

$$A_{\mathrm{PdA}} = \Delta_{\mathrm{PdA}} e^{i\varphi} \hat{\mathbf{d}} (\hat{\mathbf{m}} + i b \hat{\mathbf{n}})$$
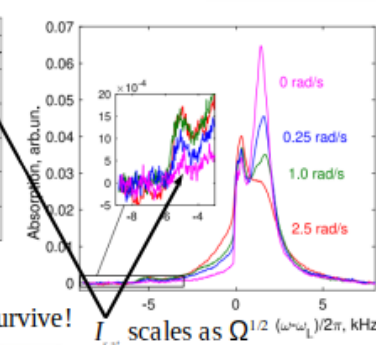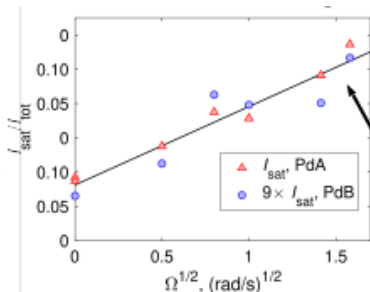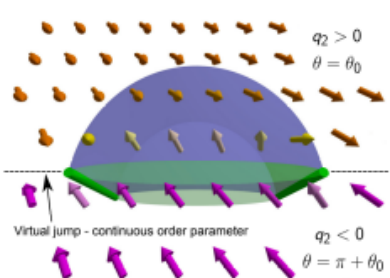
$\varphi \to \varphi + \pi, \ \hat{\mathbf{d}} \to -\hat{\mathbf{d}} \to$ OP remains singly valued $\to$ HQVs

HQVs in $(p_x + i p_y)$ PdA phase:

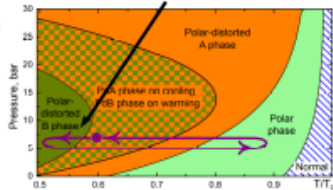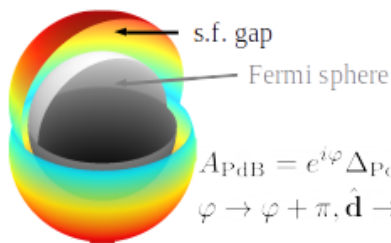[1] JTM, Dmitriev et al., Nat. Comm. **10**, 237 (2019)

Half-quantum vortex in the PdB phase

Cosmology: *Walls bounded by strings,*

Kibble, Lazarides & Shafi, PRD **26** (1982)

HQVs prohibited, but survive!

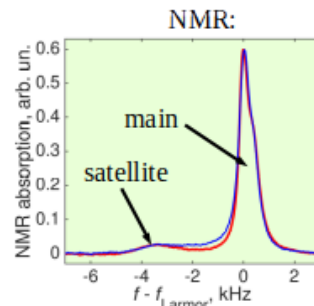I_{sat} scales as $\Omega^{1/2}$

$\rightarrow$ from *d*-solitons!

s.f. gap

Fermi sphere

$$A_{PdB} = e^{i\varphi}\Delta_{PdB}(\hat{\mathbf{d}}\hat{\mathbf{z}} + q_1\hat{\mathbf{e}}_1\hat{\mathbf{x}} + q_2\hat{\mathbf{e}}_2\hat{\mathbf{y}})$$

$$\varphi \rightarrow \varphi + \pi, \hat{\mathbf{d}} \rightarrow -\hat{\mathbf{d}}, \hat{\mathbf{e}}_1 \rightarrow -\hat{\mathbf{e}}_1, \hat{\mathbf{e}}_2 \text{ fixed: } q_2 \rightarrow -q_2$$

NMR:

main

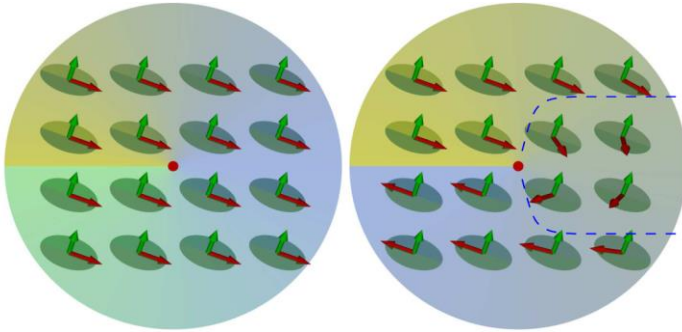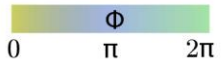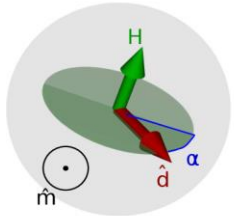satellite

Walls bounded by strings in PdB phase:

[1] JTM, Dmitriev et al., Nat. Comm. **10**, 237 (2019)

[2] Zhang, Phys. Rev. Research **2**, 043356 (2020)
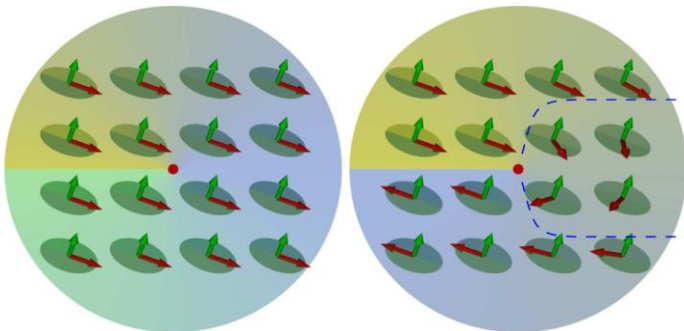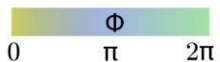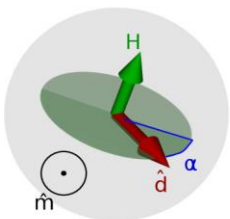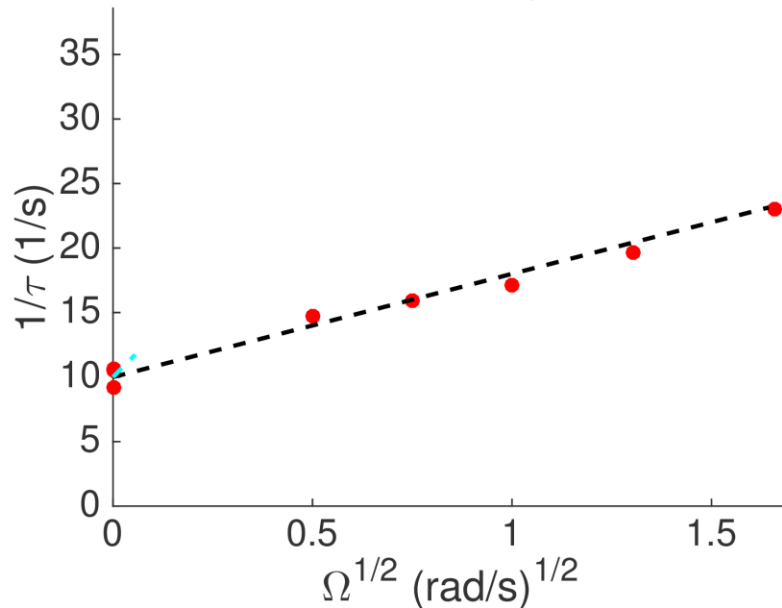
Single-quantum vortex?

Single-quantum **Half-quantum**
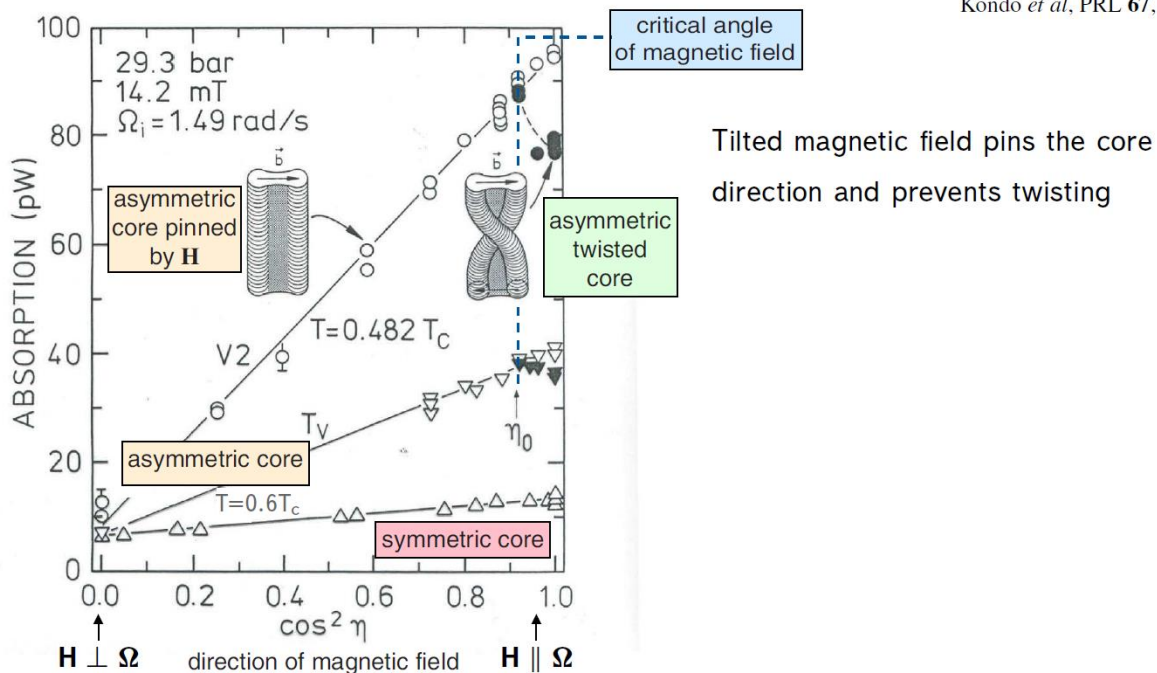
Single-quantum vortex?

Single-quantum **Half-quantum**

HPD relaxation, SQVs
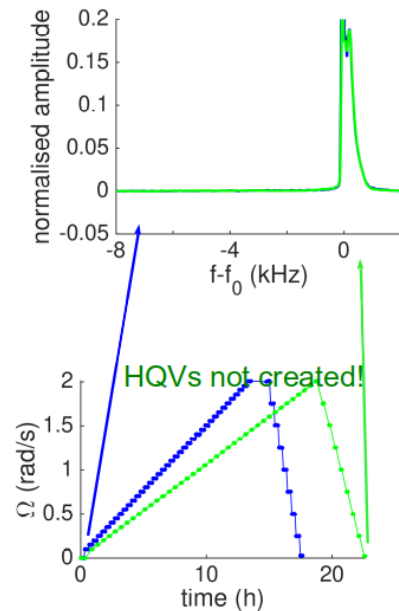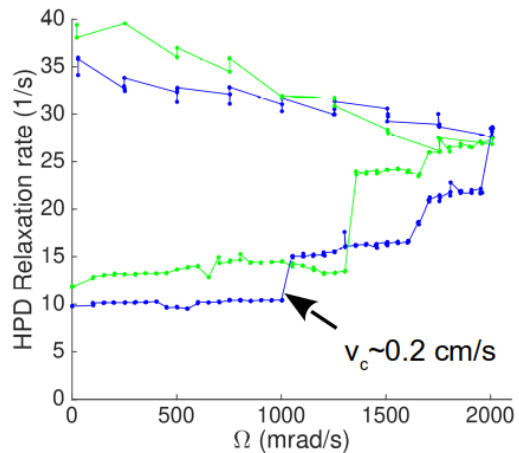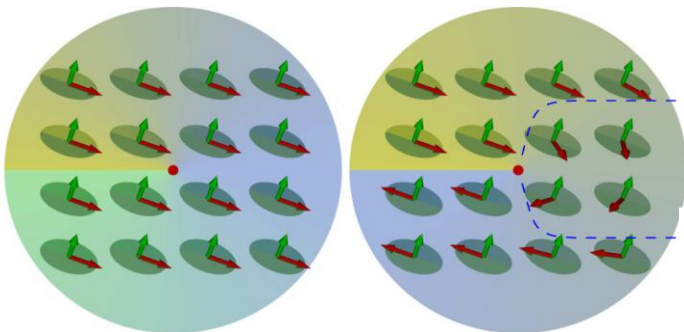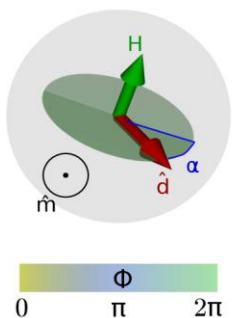
Double-core vortex detected with HPD

Twisting is observed as decrease of vortex contribution to the relaxation rate of magnon BEC.

Kondo *et al*, PRL **67**, 81 (1991)

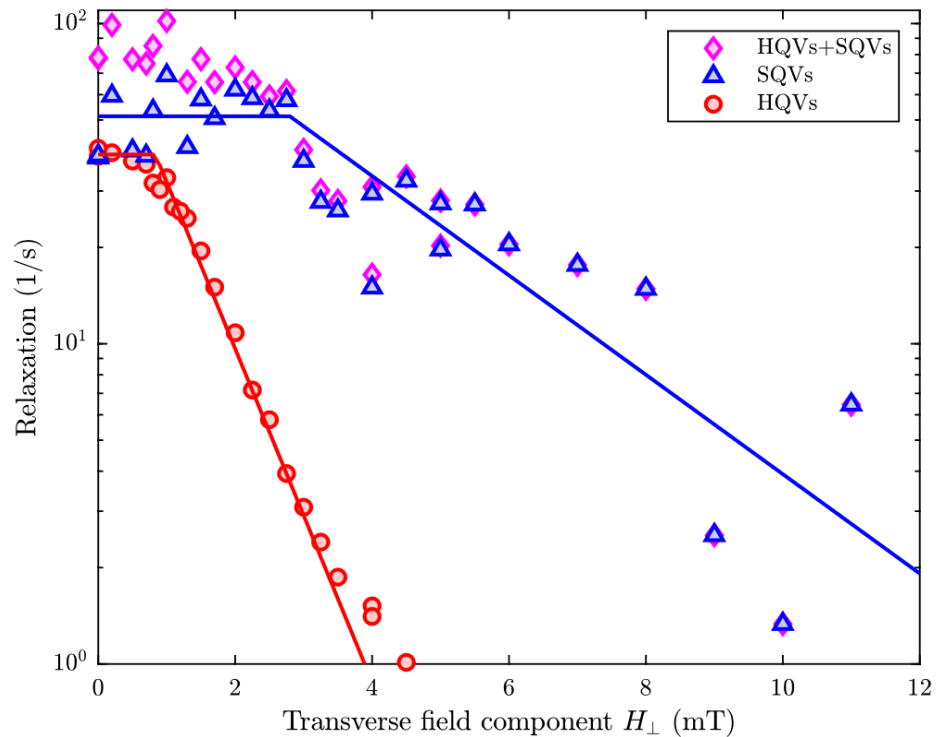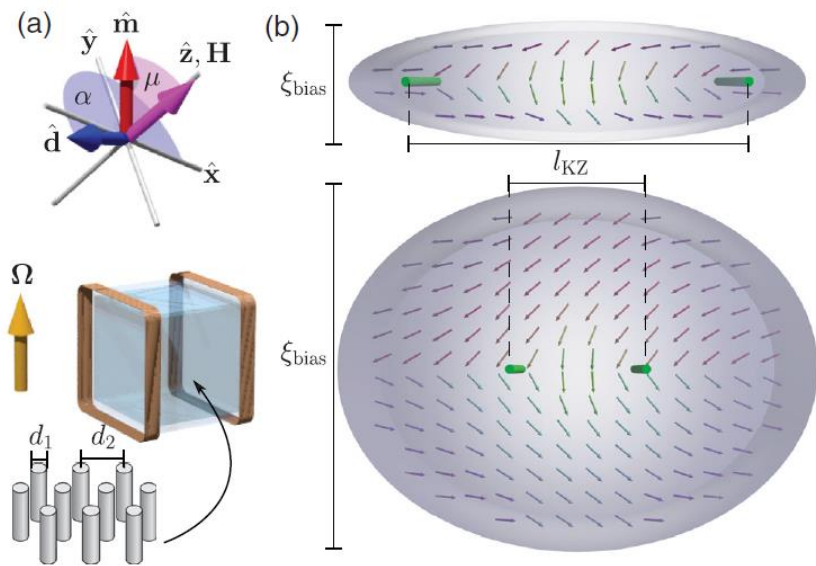Tilted magnetic field pins the core direction and prevents twisting

Single-quantum vortex?

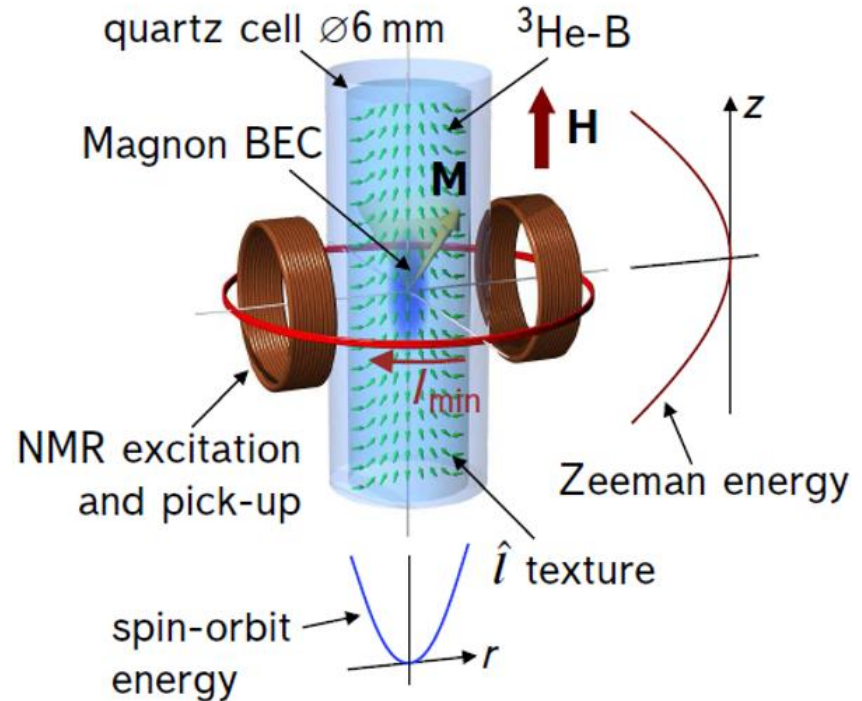**Single-quantum**   **Half-quantum**
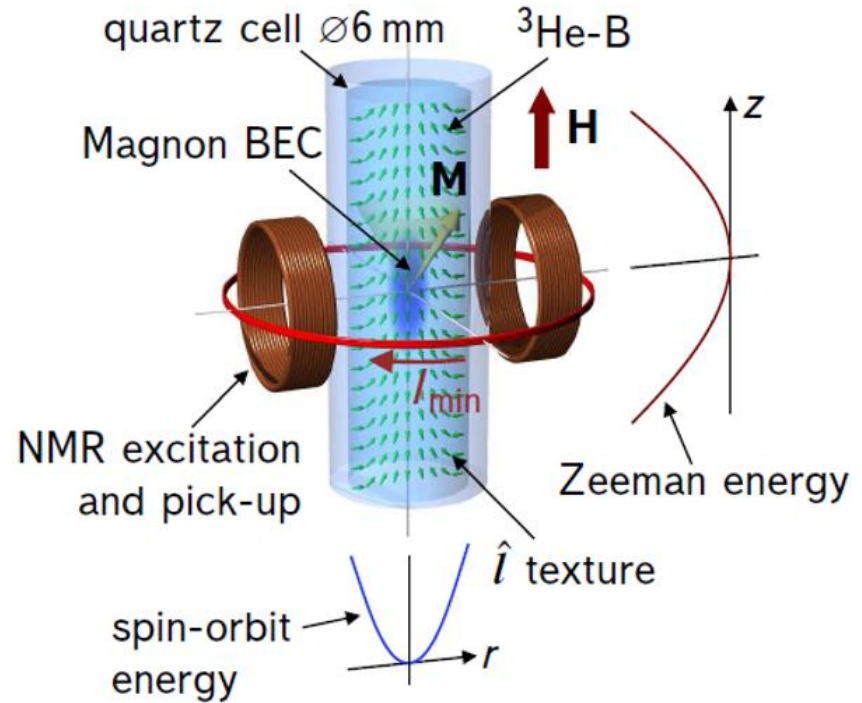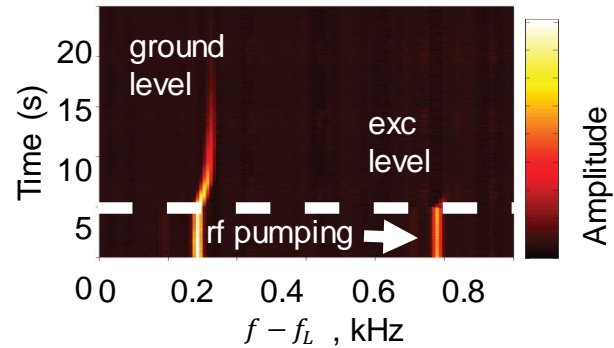
Kibble-Zurek suppressed with bias

Trapped magnon BEC

PRL 108, 145303 (2012)
JETP letters 95, 544-548(2012)
JLTP 175 , 3-16 (2014)
JLTP 175 , 681-705 (2014)
JETP letters 101, 802-807 (2015)
Nature Communications 7, 1-6 (2016)
PRB 97, 014518 (2018)
PRL 120, 215301 (2018)
PRL 121, 025303 (2018)
Nature Materials 20, 171-174 (2021)
PRR 3, L032002 (2021)
Nature Communications 13, 1-9 (2022)

quartz cell ⌀6 mm ^{3}He-B

Magnon BEC   **H**   z

M

NMR excitation and pick-up l_{min} Zeeman energy

$\hat{l}$ texture

spin-orbit energy   r

Trapped magnon BEC

Time Crystal?

Time crystals:
E.7 S.14 (1976)

Time Crystal?

Time crystals:
E.7 S.14 (1976)

F. Wilczek in PRL **109**, 160401 (2012)

Time Crystal?

Time crystals:
E.7 S.14 (1976)

F. Wilczek in PRL **109**, 160401 (2012)

J. Davis   J. Pöllänen

Time Crystal?

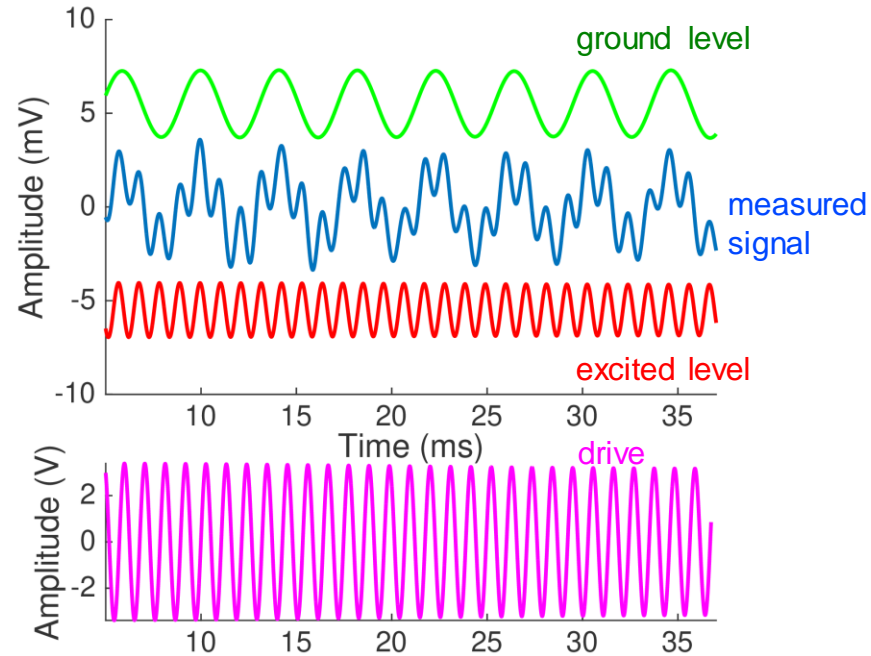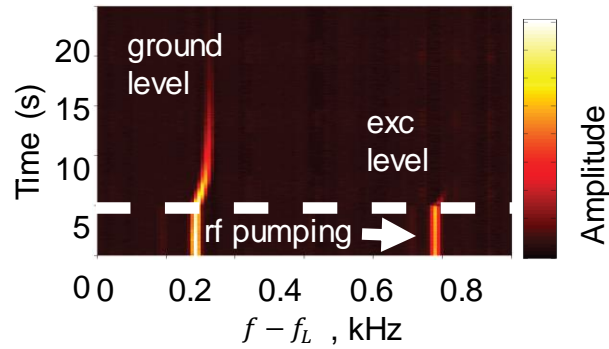Time crystals:
E.7 S.14 (1976)

F. Wilczek in PRL **109**, 160401 (2012)

- Phase of matter in repeating periodic motion
- Spontaneous period
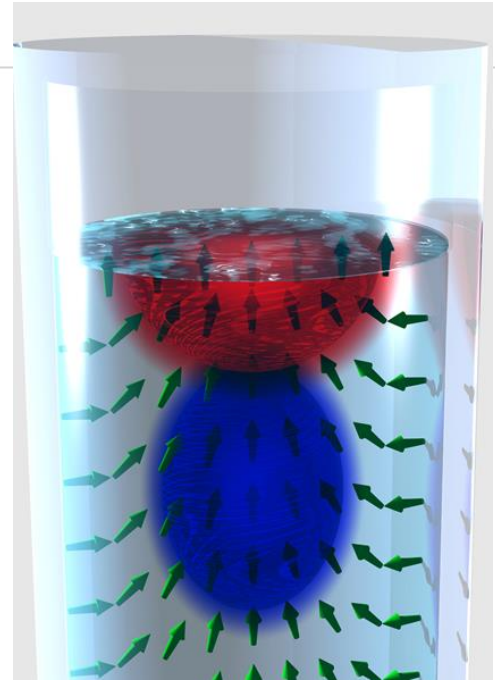- Cannot be observed in equilibrium (perpetual motion machine)

 ---> pumped / quasi-equilibrium many-body systems if observable

Time quasicrystal and continuous time crystal
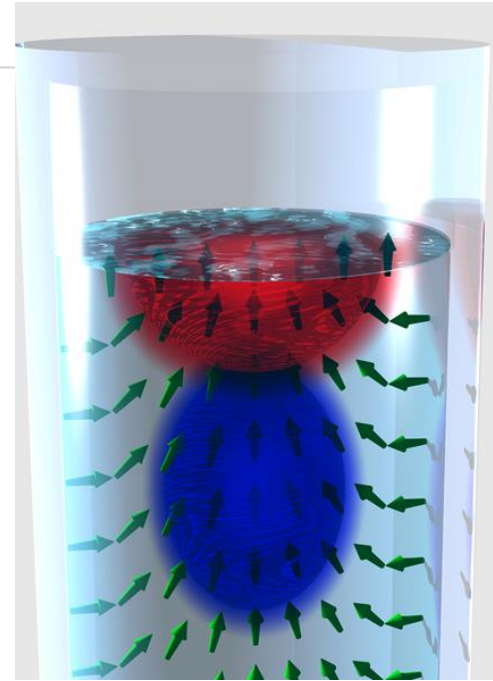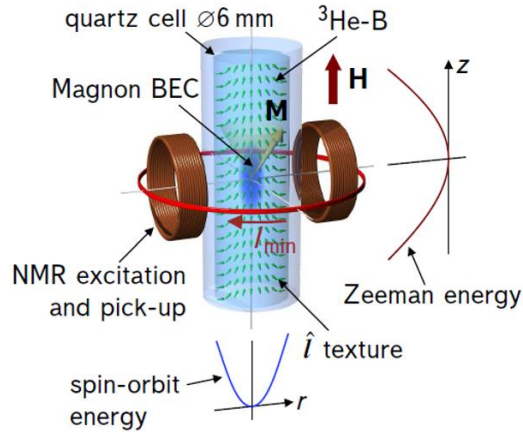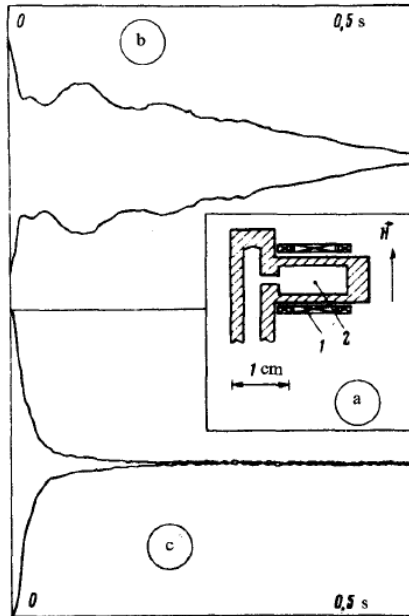
Time crystal two-level system

$$\mathcal{H} = \hbar \begin{pmatrix} \omega_{\mathrm{B}}[N_{\mathrm{B}}(t)] & -\Omega \\ -\Omega & \omega_{\mathrm{S}} \end{pmatrix}$$

HPD, Magnon BEC or Time Crystal?

Nature M **20**, 171-174 (2021)
Nature Comms **13**, 3090 (2022)

Borovik-Romanov, et al, JETP Lett, 1984

$$\mathcal{H} = \hbar \begin{pmatrix} \omega_{\mathrm{B}}[N_{\mathrm{B}}(t)] & -\Omega \\ -\Omega & \omega_{\mathrm{S}} \end{pmatrix}$$

Thank you

Kondo *et al*, PRL **67**, 81 (1991)

UNTWISTED CORE   TWISTED CORE

DISSIPATION

Bound pair of HQVs, distance $\approx \dfrac{m^*}{m}\xi$ STATIONARY VORTEX